BORON NITRIDE SOLID STATE NEUTRON DETECTOR

STATEMENT OF GOVERNMENT INTEREST

BACKGROUND OF THE INVENTION

The invention is directed to an apparatus for neutron detection wherein

neutrons are detected by measuring current pulses produced by interaction

10   of neutrons with boron nitride. The invention has particular application to

the detection of thermal neutrons.

Current neutron electronic detector systems rely principally on tubes

filled with gases such as ^{3}He and BF_3. These tubes are inefficient, bulky,

fragile and complex to manufacture. Moreover, the low density of the gas

15   phase is a major limitation on their use. Additionally, these prior art tubes

have slow response times and are incapable of high resolution position

sensing.

Generally, semiconductor detectors of nuclear radiation operate by

exploiting the fact that incident radiation, by interaction in the detector

20   volume, will create a charge pulse consisting of holes and electrons that can

be separated under the influence of an electric field and the current detected

by an external circuit. The conversion efficiency of solid state detectors is

typically 100 to 1000 times greater than that of conventional gas-filled tubes

consequently, solid state detectors are more sensitive than conventional

25   gas-filled tubes. Moreover, solid state detectors are generally more

compact, robust, and reliable than their gas-filled counterparts.

Newacheck et al. in U.S. Patent No. 5,334,840 have shown that carbon infiltrated hexagonal boron nitride (hBN) can be used as a thermal neutron detector. The hexagonal boron nitride is used as a scintillator, to produce light in response to neutron conversion. The light is then detected in a

5   secondary process, such as by exposing a photographic emulsion, or electronically with a photomultiplier or some other photon detection device. While this approach can be very efficient, timing and discrimination against gamma rays are poor. Moreover, detection relies on secondary means for detection rather than by a more efficient direct process.

10   SUMMARY OF THE INVENTION

Accordingly, the present invention provides for direct detection of neutrons by measuring the current produced when neutrons interact with hexagonal born nitride (hBN).

                         BRIEF DESCRIPTION OF THE DRAWINGS

15   Figure 1 compares the density of conversion atoms in solid hBN versus gas-filled tubes illustrating the improvement in sensitivity achieved by substituting a solid conversion medium for a high pressure gas.

Figure 2 shows the ionization profile for thermal neutron conversion in hBN.

20   Figure 3 illustrates a typical measurement circuit for converting neutrons to an electronic signal.

Figure 4 shows typical neutron response waveforms obtained from the circuit of FIG. 3.

Figure 5 is a pulse height histogram in a thermal neutron flux 7×10^5

25    $n/cm^2/s$ for thermal neutron conversions in hBN.

Figure 6 is a pulse height histogram for ^{241}Am alpha particles in hBN.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to an apparatus for the direct detection of neutrons and particularly thermal neutrons. The apparatus operates on the principle that an incident neutron is converted into energetic

5   charged particles within a solid ionizable medium such as hexagonal boron nitride (hBN). The resulting ionization is sensed by direct collection of the charge carriers in the medium.

FIG.1 illustrates the improvement in efficiency provided by the invention over available electronic detectors such as BF_3 and ^3He gas filled

10   tubes. The density of neutron converting ^{10}B atoms in hBN is greater by a factor of 100 to 1000 compared to typical high-pressure ^3He tubes, or typical BF_3 tubes operating below atmospheric pressures.

Neutrons interacting in the solid are absorbed by ^{10}B atoms, causing a nuclear reaction liberating 2.3 to 2.8 MeV of energy in the form of kinetic

15   energy of the reaction products, ^7Li and ^4He. These particles ionize the surrounding material, resulting in free charge carriers distributed about the converting atom as seen in FIG.2. The asymmetric bimodal distribution is caused by the two dissimilar mass particles (^7Li and ^4He) traveling in opposite directions to conserve momentum. The more massive lithium ion

20   produces the peak on the left, while the ^4He particles produce the peak on the right. As seen in FIG. 2, the centroid of ionized charge is distributed within a few microns of the converting atom, enabling position sensitive detection with very high spatial resolution in contrast to prior art devices. For example, the centroid of the charges is displaced only 1.2 microns from

25   the converting atom, making 2.4 micron spatial resolution possible in principle. In comparison, ionized charge distributions in prior art neutron

gas detectors typically span millimeters.

The result of neutron interaction described above is a detectable current pulse. In the invention, the ionizable medium is hexagonal boron nitride (hBN), and preferably pyrolytic hexagonal boron nitride. The material

5   of the present invention may be a single crystal, or it may be disordered. For example, the material may be a polycrystalline aggregate or a layered structure, refer to as "turbostatic," which exhibits long range crystallographic order in that the hexagonal crystallographic c axis in each layer is generally aligned in a common direction. Current pulses produced by conversion of

10   the incident neutrons to energetic charged particles are detected by applying an electric field to the of the hBN detector body in a direction about perpendicular to the crystallographic c axis.

A typical measurement circuit **300** that can be used for detecting a neutron conversion event as described above is shown in FIG. 3. In this

15   circuit a voltage from a power supply means **310** is applied across hBN material **320** by electrodes **315**. Carriers created by the neutron conversion event are drifted some distance within the hBN material **320**, resulting in a fast current pulse. The current is integrated across capacitor **312** in charge sensitive preamplifier **325**. This step-function pulse is then amplified and

20   shaped by spectroscopy amplifier **330** to reduce noise and false triggering of measurement circuit **300**. This shaped pulse is then used to trigger a signal measuring means **340**, such as an oscilloscope (not shown) or some other measurement or recording device, such as a multichannel analyzer.

The measurement circuit described above was used to study hBN

25   exposed to various forms of radiation. A body of hBN **320** disposed between electrodes **315** was exposed to a thermal neutron flux of about 7×10^5 $n/cm^2/s$

from a nuclear reactor. The body of hBN was about 0.35 mm thick and about

2 mm on a side. A voltage of about 1 kV was applied to the electrodes

disposed about perpendicular to the c axis of the hBN body by power supply

means **310** and a signal of about 2 mV was detected and measured by

5   associated signal measuring means **340**, described above. Typical pulse

results captured using a digital oscilloscope are shown in FIG. 4. The hBN

material exhibited a rise time of less than about 100 ns. It will be

appreciated by those skilled in the art, that rise times of this magnitude

enable counting rates greater than about 10^6 counts/sec. and timing

10   resolution of less than about 10 ns. In comparison, conventional ^{3}He

detectors generally exhibit 1 μs timing and count rates of 10^5 counts/sec.

The pulse height distribution recorded for this experiment is seen in

FIG. 5. A count rate of about 10^2 counts/sec. was observed in this

experiment. However, when a boron shutter was interposed between the

15   reactor and the hBN neutron detector device the count rate dropped to

virtually zero. These results show that the device is sensitive to thermal

neutrons, but is insensitive to the gamma radiation produced by the reactor.

The estimated quantum efficiency of this device, made from natural hBN,

was about 8%. The estimated efficiency for a similar device made from

20   boron enriched to a level of 100% with the isotope ^{10}B should be about 44%,

comparable to the best ^{3}He gas tubes.

FIG. 6 shows a similar pulse height spectrum taken with the device of

the present invention during exposure to alpha particles from an isotopic

source. An important new feature emerges from the data when the two

25   spectra shown in FIGs. 5 and 6, are compared. Whereas the isotopic alpha

particles have approximately twice the energy of the conversion products

(5.4 MeV versus 2.8 MeV), the pulses produced are similar in magnitude. These results show that ionization from neutron reaction products (^{7}Li and ^{4}He) produce signals in the device more effectively than alpha particles (^{4}He) alone.

5   Additional testing was done with 3.4 MeV protons (^{1}H) from an accelerator. When these protons were directed on the device of FIG. 3, no detectable signal was produced. In consideration of the above results, it is clear that the both the energy deposited (E) and the rate of energy deposition ($\frac{dE}{dx}$) are important in generating a signal in the device of the

10   invention. Therefore, the insensitivity to gamma radiation from the nuclear reactor is due not only to the low atomic numbers of the constituents of the hBN, but to the existence of a $\frac{dE}{dx}$ threshold. This threshold is between the maximum $\frac{dE}{dx}$ for a proton (^{1}H) and that of an alpha particle (^{4}He). The lower bound for this threshold is about 12 eV/Angstrom, and is indicated as a

15   horizontal line in FIG. 2.

         It should be noted that this effect can be attributed to the existence of a high density of trap states in the material. These traps act to immobilize charge carriers, removing them from the signal. Lower mass particles, such as photoelectrons and protons, generate lower concentrations of mobile

20   charge carriers. These carriers are quickly trapped, effectively eliminating the signal. Higher mass particles such as helium and lithium ions interact more strongly in the material, producing concentrations of mobile carriers far in excess of the trap density. The carriers therefore saturate the traps and generate detectable current pulses.

25   This trapping results in a threshold effect, which can be used to

discriminate between particles strictly according to their masses. Many

materials could be modified to introduce such a threshold. Semiconductors

including silicon, germanium, gallium arsenide, and cadmium telluride exhibit

trapping in varying degrees caused by intrinsic and extrinsic defects (e.g.

5   vacancies or impurity atoms) and by extended defects such as stacking

faults and dislocations. Certain polymers can also behave in this way (e.g.

poly(3-octylthiophene), poly(2,5-dioctyloxy-p-phenylenevinylene) (DPOOPPV)

and poly(1-methoxy-4-(2-ethylhexyloxy)-2,5-phenylenevinylene) (MEHPPV)).

It is reasonable to expect that a dE/dx threshold could be induced in these

10   materials by introducing high concentrations of the above defects. It is also

reasonable to extend this effect to scintillators, which rely on the same

mobile charge carriers to diffuse and recombine at centers distributed in the

material. Examples include cesium iodide, sodium iodide and anthracene.